



# An optoelectronic cw THz source for imaging applications

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**Abstract** – We report on optoelectronic generation of continuous-wave (cw) THz radiation from a two-colour Ti:sapphire laser source. The laser emits two beams with a frequency difference between 1 GHz and 50 THz simultaneously. For the photomixing of the two frequencies, planar dipole and microstrip patch antennas based on low-temperature-grown (LT-)GaAs are examined. THz powers up to 60 nW at 450 GHz are achieved. Potential applications of this cw THz source for imaging are discussed.

## I. INTRODUCTION

Application of optoelectronically generated THz radiation in imaging has recently been identified to be a realistic goal of research [1,2]. All THz imaging work up to now has been performed with femtosecond laser systems. However, cw THz systems can be advantageous because of the following reasons: (i) They can be operated with laser diodes which implies a reduction in cost, size and complexity of the laser source. From a commercial point of view this is the main advantage over conventional femtosecond-laser-based systems. (ii) In addition, cw systems have technological advantages such as their higher spectral brightness in combination with a better frequency resolution. The latter stems from the fact that the frequency stability of the emitted radiation and thus the spectral resolution of the cw system is limited by the frequency stability of the laser source (typically  $\sim 100$  kHz), whereas for pulsed systems the frequency resolution is given by the scanned length of the delay line (the resolution is approx. 1 GHz for 15-cm scan length). (iii) Last but not least, data acquisition with cw systems has the prospect of being less time-consuming as no Fourier transformation or pattern recognition is needed to obtain information for a specific frequency. On the other hand, obtaining wide-band spectra is and remains the strong point of femtosecond-laser-based THz systems.

Heterodyne downconversion, or photomixing, of two infrared optical frequencies is a promising way to gene-

rate tunable cw electromagnetic radiation in the GHz and THz frequency bands. Previous investigations mainly focused on two independent laser sources [3,4] or two-colour diode lasers [5,6] for photomixing.

We present a Ti:sapphire laser which emits two near-infrared beams from a single cavity. Both beams can be tuned independently over a wavelength range of 100 nm which corresponds to difference frequencies from below 1 GHz up to 50 THz. The total output power is on the order of 250 mW at a pump power of 6 W. The photomixer is a planar photoconductive antenna with an ultrafast switch based on LT-GaAs and either a Hertzian dipole or a microstrip patch antenna as the radiating element.

We present an investigation of a measurement set-up basically suited (but not optimized yet) for cw THz imaging with a bolometer as a detector.

## II. LASER SYSTEM

The two-colour laser is pumped by a single beam of an argon-ion laser operated in all-lines mode with an output power of 6 W. Figure 1 shows the linear,  $\alpha$ -shaped resonator with a round-trip length of 1.36 m (corresponding to a 219.5-GHz spacing of the longitudinal modes).

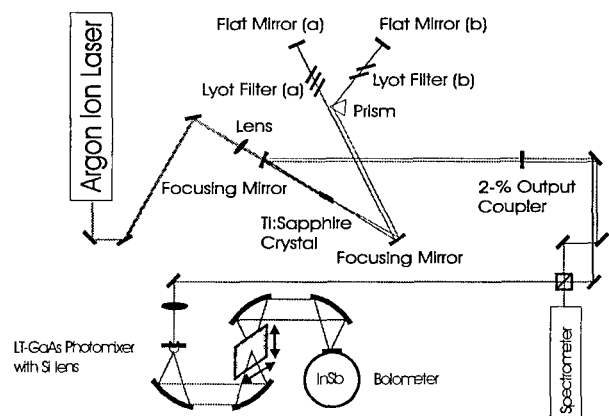


Fig.1: Two-colour Ti:sapphire laser with photomixing set-up in THz-imaging configuration

The laser cavity [7] consists of five mirrors, three of them being shared by both beams while two mirrors in the wavelength-selection segment are used by either beam only. Under all operation conditions, laser action with a circular  $TEM_{00}$  Gaussian mode profile showing no sign of astigmatism is achieved. The two colours are emitted in parallel, but non-collinear beams. Beam (a) is

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tuned with a three-plate Lyot filter, beam (b) with a two-plate filter and a prism. The wavelength tuning curve is given in Fig. 2.

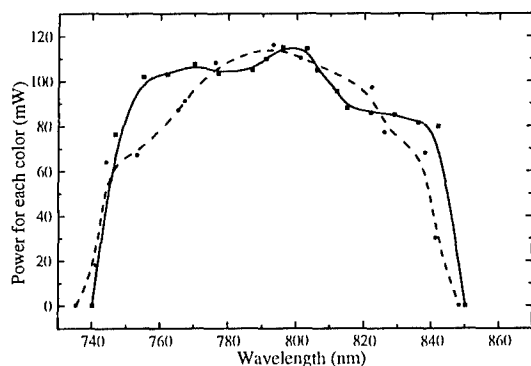


Fig. 2: Tuning spectrum of the two-color Ti:sapphire laser. Solid line: One frequency is fixed at 800 nm the other is tuned; Dotted line: Both frequencies are tuned with a fixed wavelength difference of 7 nm.

The solid line displays the tuning characteristics which can be achieved if one frequency is kept fixed at 800 nm. The dotted line is taken while both frequencies are tuned with a fixed wavelength difference of 7 nm between them. From interference measurements (see [7]), we obtain a FWHM width of each of the two optical lines of less than 150 MHz which suggests that the laser runs predominantly on a single longitudinal mode.

The data shown in Fig. 2 are obtained with a 2-% output-coupling mirror in the resonator. Replacing it with a 4-% output coupler increases the output power to 125 mW per beam in the central part of the spectrum.

### III. PHOTOMIXING

For the first demonstration of photomixing applying the two-colour Ti:sapphire laser, we fabricated a planar Hertzian-dipole antenna on LT-GaAs. The antenna layout is shown schematically in Fig. 3. It is a design as often utilized in femtosecond THz systems.

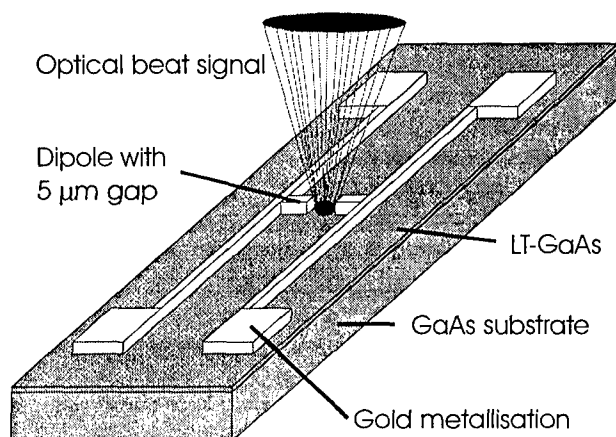


Fig. 3: Planar Hertzian-dipole photoconductive antenna on LT-GaAs

The antenna is made from thermally evaporated chromium/gold and patterned by photolithography and photo-

resist lift-off. The dipole length is chosen to be 50  $\mu\text{m}$  yielding resonance of the antenna just above 1 THz. The dipole has a 5- $\mu\text{m}$ -gap which serves as a photoconductive switch. On the substrate side of the antenna, a Si lens is mounted to collect the emission from the radiating structure. In order to drive the antenna at the optical beat signal, the two infrared beams emitted by the two-colour Ti:sapphire laser have to be overlapped on a beam combiner (see Fig. 1). The laser radiation is then focused with a 2-cm lens onto the photoconductive switch. For the detection of the THz radiation, we apply an InSb hot-electron bolometer.

Due to the bandwidth limitations of the InSb bolometer, THz signals can only be measured up to 460 GHz. This is far below the resonance frequency of the antenna. At 460 GHz, about 0.02 nW of THz power (calibration of the bolometer) is measured for an optical pump power of 55 mW and a bias voltage of 25 V applied to the switch.

A more promising device in terms of the emitted power was developed based on an emitter concept known from the very first experiments on the generation of GHz radiation by photomixing of two infrared beams by Brown et al. [8]. The layout of our device can be described as a microstrip patch antenna and is displayed in Fig. 4.

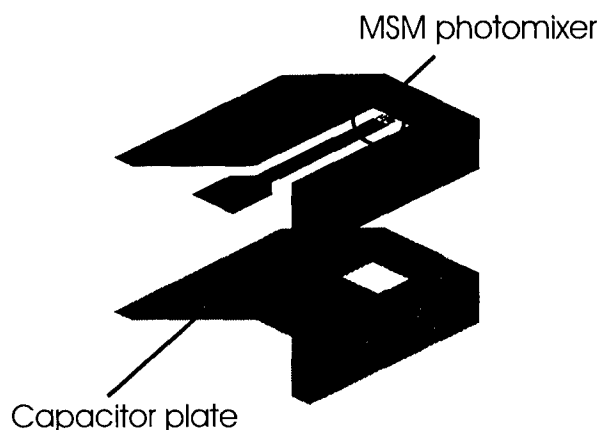


Fig. 4: Exploded view of the folded microstrip patch antenna with metal-semiconductor-metal (MSM) interdigitated photoconductive switch

In the work described in [8], operation of the photomixer was limited to frequencies up to 50 GHz due to constraints in the design and size of the device which were determined by the fact that the measurements were made with a HF spectrum analyser connected to the device via a coaxial cable. In contrast, we perform free-space measurements and are free from these limiting factors in the design.

While the emitter of [8] consists of a single planar metal structure, our emitter is based on a capacitor-like double-layer design. Details concerning the emitter can be found in [9]. Briefly summarized: The top layer is a coplanar waveguide structure whose centre conductor is in Ohmic contact with the bottom layer; otherwise, the two layers are separated from each other by a 1- $\mu\text{m}$ -thick polyimide film. The photoconductive switch is located at one end of the coplanar waveguide. It consists of four-finger interdigitated electrodes which are defined on a LT-GaAs epi-

taxial layer transferred by lift-off technology from the GaAs growth substrate onto a glass substrate. The width of the metal fingers is 3  $\mu\text{m}$ , the distance between adjacent fingers is also 3  $\mu\text{m}$ .

When excited with the far-infrared beat signal, the device exhibits a pronounced resonance in the emission spectrum at 439 GHz (for the data, see [9]). The resonance curve has a FWHM of 55 GHz. The THz power emitted at resonance is on the order of 60 nW for 9-mW optical pump power and a bias of 20 V.

The patch antennas investigated so far were processed by epitaxial lift-off onto a glass substrate. As a result of the low heat conductivity of glass, the MSM switch was thermally damaged when the optical power exceeded 10 mW. If left on the semiconductor growth substrate, the MSM photomixers should sustain optical powers up to 70 mW [10]. This fact clearly points the way toward further improvements of the emitter.

The tunability of the device is clearly limited due to its resonant behaviour. For wide-band imaging applications, this may seem to be a disadvantage. One has to keep in mind, however, that a narrow-band emitter can be optimized for both higher maximum output power and better noise rejection than a wide-band radiator. With different mixers designed for various discrete frequencies of interest, one can achieve a broad wavelength coverage while keeping the advantages of a narrow-band emitter.

#### IV. CW THZ IMAGING

For the first tests of THz imaging with a cw system we employ a set-up as shown in Fig. 1. Behind the photomixer, the divergent radiation is collimated and focused onto the sample with two off-axis paraboloidal mirrors. The radiation transmitted through the sample is collected by another set of paraboloidal mirrors and focused into the bolometer.

The object to be imaged can be raster-scanned in the focus of the THz beam with the help of a x-y-stage while recording the transmittivity at each pixel with the InSb bolometer. The first structures which we have examined are various objects consisting of THz-absorbing materials like metal and carbon (data to be published elsewhere). Our measurements indicate that intensity-contrast imaging with cw THz radiation is feasible and that it takes no more time to obtain an image than with femtosecond-laser-based systems.

Due to the relatively large wavelength at frequencies below 450 GHz, the spatial resolution is still rather poor. This will change, when higher frequencies are accessible upon replacement of bolometric detection by coherent homodyne detection, i.e., photoconductive [11] and electrooptic sampling [12].

#### V. CONCLUSIONS

We presented a two-colour Ti:sapphire laser which emits two near-infrared beams simultaneously with a maximum output power of 250 mW for both colours together. The difference frequency is tuneable from 1 GHz to 50 THz. We have demonstrated photomixing with a photoconductive switch integrated into either a Hertzian-dipole antenna or a microstrip patch antenna. For the patch antenna, we achieve a THz output power of 60 nW at 439

GHz, when pumped with 9 mW of optical power. Finally, the principal suitability of our cw measurement systems for THz imaging was corroborated.

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